Violation of Equivalence Principle and Solar Neutrinos *

A. M. Gago[a,b], H. Nunokawa[c] and R. Zukanovich Funchal[b]

[a] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú
Apartado 1761, Lima, Perú

[b] Instituto de Física, Universidade de São Paulo C. P. 66.318, 05389-970 São Paulo, Brazil

[c]Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, UNICAMP
13083-970 Campinas SP, Brazil

We have updated the analysis for the solution to the solar neutrino problem by the long-wavelength neutrino oscillations induced by a tiny breakdown of the weak equivalence principle of general relativity, and obtained a very good fit to all the solar neutrino data.

1. INTRODUCTION

It is considered that the results coming from atmospheric neutrino experiments [1], as well as solar neutrino experiments [2–6], are strong evidence of neutrino oscillation indicating the presence neutrino mass and flavor mixing. However, several alternative explanations to these results, which do not invoke neutrino mass and/or mixing, exist and are not yet excluded [7].

The interesting idea that gravitational forces may induce neutrino mixing and flavour oscillations, if the weak equivalence principle of general relativity is violated, was proposed about a decade ago [8,9], and thereafter, many works have been performed on this subject [10].

Many authors have investigated the possibility of solving the solar neutrino problem (SNP) by such gravitationally induced neutrino oscillations [11], generally finding it necessary, in this context, to invoke the MSW like resonance [9] in order reduce appropriately the solar neutrino fluxes with the specific energy dependence, required to explain the data. Nevertheless we have demonstrated in Ref. [12] that all the recent solar neutrino data coming from gallium, chlorine and water Cherenkov detectors can be well accounted for also by long-wavelength neutrino oscillations induced by a violation of the equivalence principle (VEP). In this talk, we present updated fit of such gravitationally induced long-wavelength oscillation solution [12,13] to the most recent solar neutrino data which include the first GNO measurement [5].

2. THE VEP FRAMEWORK

We follow the framework proposed in Refs. [8, 9]. In the presence of violation of equivalence principle, neutrino mixing and oscillation can occur even if neutrinos are massless. In this work we assume oscillations only between two species of neutrinos, which are massless (or degenerate in mass), either between active and active ($\nu_e \leftrightarrow \nu_\mu, \nu_\tau$) or active and sterile ($\nu_e \leftrightarrow \nu_s$, ν_s being an electroweak singlet) neutrinos.

To describe the VEP induced massless neutrino oscillation mechanism, phenomenologically, we can simply do the following replacement in the usual mass induced oscillation formula: $\Delta m^2/2E \rightarrow 2E|\phi\Delta\gamma|$ and $\theta \rightarrow \theta_G$, where Δm^2 is the mass squared difference, ϕ is the gravitational potential which is assume to be constant in our work, θ is the usual mixing angle which relate weak and mass eigenstates and θ_G is the mixing which relates weak and gravitational eigenstates, and $\Delta\gamma$ is the quantity which measures the mag-

*Talk presented by H. Nunokawa at Europhysics Neutrino Oscillation Workshop (NOW2000), Otranto, Italy, September 9-16, 2000

nitude of VEP.

The survival probability of ν_e produced in the Sun after traveling the distance L to the Earth is given by,

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_G \sin^2 \frac{\pi L}{\lambda}, \tag{1}$$

where the oscillation wavelength λ for a neutrino with energy E is given by

$$\lambda = \left[\frac{\pi \text{ km}}{5.07}\right] \left[\frac{10^{-15}}{|\phi\Delta\gamma|}\right] \left[\frac{\text{MeV}}{E}\right], \tag{2}$$

which in contrast to the wavelength for mass induced neutrino oscillations in vacuum, is inversely proportional to the neutrino energy. This energy dependence is very crucial in obtaining a good fit to the total rates without causing any problem with the SK spectrum [12].

3. ANALYSIS

We present here the results of our analysis only for active to active conversion since the results are qualitatively similar for active to sterile one [12].

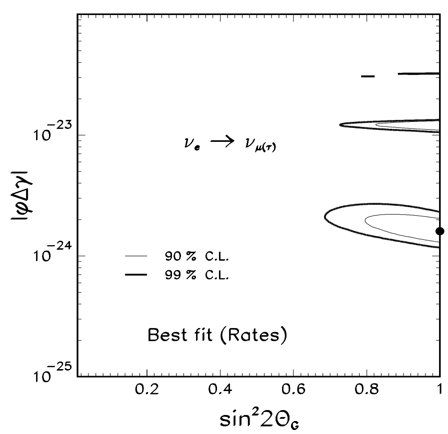

Fig.1: Parameter region of $\sin^2 2\theta_G$ and $|\phi\Delta\gamma|$ allowed by the total rates only for $f_B = 1$. The best fit point is indicated by the filled circle.

We performed the same statistical analysis as we did for three flavor vaccum oscillation solution to the SNP in Ref. [14], which is slightly different from our analysis in Ref. [12]. We fit VEP parameters $|\phi\Delta\gamma|$ and θ_G, and an extra normalization factor f_B for the ^{8}B neutrino flux, to the most recent experimental results coming from Homestake [2], SAGE [3], GALLEX [4] and GNO [5] combined, and Super-Kamiokande (SK) [6].

We present in Fig. 1 the allowed region determined only by the total rates for fixed ^{8}B flux. We then present in Fig. 2 the result for spectral shape analysis fitting only the ^{8}B spectrum measured by SK [6] in the same way as we did in Ref. [14].

Finally, we perform a combined fit of the rates and the spectrum obtaining the allowed region presented in Fig. 3. The combined allowed region is essentially the same as the one obtained by the rates alone. We also show in Fig. 4, the predicted spectra for the best fitted parameters, which are in good agreement with the data.

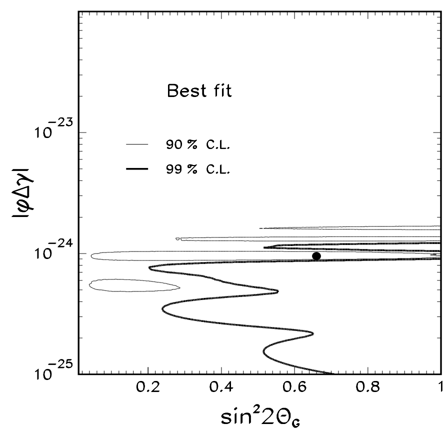

Fig. 2: Same as in Fig. 1 but for SK recoil electron spectrum. It is the inner part of the contours which is excluded by the data.

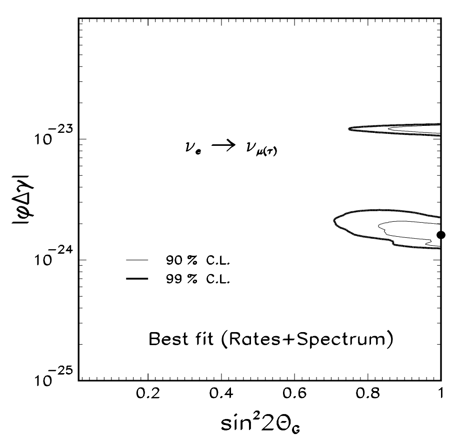

Fig. 3: Same as in Fig. 1 but for the rates and SK spectrum combined.

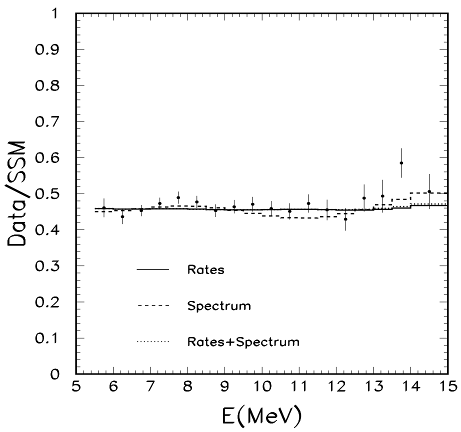

Fig. 4: Expected spectrum for the best fitted parameters.

Best fitted parameters as well as $\chi^2_{\rm min}$ can be found in Table I. From this table, we can conclude that the fit is quite good. For sterile conversion, we found somewhat worse, but acceptable, fit compared to the active one. For example, we found for the combined fit, $\chi^2_{\rm min} = 19.5$ for 24 D.O.F. for fixed f_B.

Table 1
The best fitted VEP parameters and values of $\chi^2_{\rm min}$. Values of $|\phi\Delta\gamma|$ are shown in units of 10^{-24}. Number of degree of freedom are from top to bottom, 2, 1, 15, 24 and 23. f_B is fixed unless it is indicated as "free" in the parenthese. We include 6 bins for the SK zenith angle dependence in the combined fit.

Case	$\sin^2 2\theta_G$	$\|\phi\Delta\gamma\|$	f_B	$\chi^2_{\rm min}$
Rates	1.0	1.60	—	1.78
Rates (free)	1.0	1.63	0.79	0.39
Spectrum	0.66	0.95	—	8.68
Combined	1.0	1.63	0.79	17.65
Combined (free)	1.0	1.63	0.79	16.3

4. SUMMARY

We have obtained a very good fit to the most recent solar neutrino data for the VEP induced long-wavelength neutrino oscillation.

Let us finally remark that, in contrast to the usual vacuum oscillation solution to the SNP, in this VEP scenario no strong seasonal effect is expected in any of the present or future experiments, even the ones that will be sensitive to ^{7}Be neutrinos. See Ref. [12] for more detail.

ACKNOWLEDGMENTS

HN thanks E. Lisi for a useful discussion during the NOW2000 workshop. This work was supported by the Brazilian funding agencies FAPESP and CNPq.

REFERENCES

1. See T. Kajita and F. Ronga in these proceedings.
2. K. Lande *et al.*, Astrophys. J. **496** (1998) 505.
3. V. Gavrin for the SAGE Collab., talk given at the XIX International Conference on Neutrino Physics and Astrophysics (Neutrino 2000), Sudbury, Canada, June 16-21, 2000, available at http://nu2000.sno.laurentian.ca/.
4. W. Hampel *et al.*, Phys. Lett. B **447** (1999) 127.
5. E. Bellotti for the GNO Collab., talk given at "Neutrino 2000" as in Ref.[3], M. Altmann *et al.*, Phys. Lett. B **490** (2000) 16.
6. See Y. Suzuki in these Proceedings.
7. See M. Lusignoli, M. M. Guzzo, T. K. Kuo, J. Pulido in these proceedings.
8. M. Gasperini, Phys. Rev. D **38** (1988) 2635; *ibid.* **39** (1980) 3606.
9. A. Halprin and C. N. Leung, Phys. Rev. Lett. **67** (1991) 1833.
10. See Ref. [12] and references therein.
11. J. Pantaleone, A. Halprin, and C. N. Leung, Phys. Rev. D **47** (1993) R4199; J. N. Bahcall, P. I. Krastev, and C. N. Leung, Phys. Rev. D **52** (1995) 1770; S. W. Mansour and T. K. Kuo, Phys. Rev. D **60** (1999) 097301.
12. A. M. Gago, H. Nunokawa and, R. Zukanovich Funchal, Phys. Rev. Lett. **84** (2000) 4035.
13. H. Casini, J.C. D'Olivo and R. Montemayor, Phys. Rev. D **61** (2000) 105004.
14. A. M. Gago, H. Nunokawa and, R. Zukanovich Funchal, Phys. Rev. D **63** (2000) 013005.